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Variability Reduction and Design of Experiments Techniques for Improving System Performance of the International Space Station Kit for External Repair of Module Impacts

Ravi I. Chaudhary¹, Rafael Moras¹, Stephen Hall², and William Bohl³

¹Department of Engineering, St. Mary's University, San Antonio, TX 78228

²Flight Projects, NASA Marshall Space Flight Center, Huntsville, AL 35812

³Sverdrup Inc., Huntsville, AL 35812

[(912)328-8320: ravichaud@aol.com]

Abstract. The Kit for Repair of Module Impacts, or KERMIIt, is designed to provide astronauts with a patch kit to seal damaged International Space Station (ISS) modules. The patch is applied externally and requires Extravehicular Activity, or space walks, in order to install the patch. The installation procedure is crew intensive and requires injection of an adhesive to form a lasting environmental seal, restoring atmospheric conditions inside the module. A five-step analysis of the KERMIIt program revealed two critical processes which, when controlled, provided measurable performance gains in the KERMIIt system. Adhesive injection and flow was the first critical process, requiring design of experiments and variability reduction techniques to reduce variability in adhesive flow and formation. Analysis of KERMIIt crew installation procedures required refinement of experimental methods in order to determine areas for improvement. Verification testing validated both control techniques, demonstrating the effectiveness of variability reduction and design of experiments to improve KERMIIt system performance.

INTRODUCTION

The Kit for Repair of Module Impacts, or KERMIIt, is a mechanical system designed by Sverdrup, Inc. for the National Aeronautics and Space Administration. It's primary function is to temporarily repair small to medium size damage holes in the in the International Space Station. Using advanced Extravehicular Activity techniques, or space-walks, NASA Astronauts install the KERMIIt patch directly over the penetration hole, and inject an optimized epoxy based adhesive, creating a lasting seal in the penetration hole. Since KERMIIt is a highly developmental mechanical system, considerable effort was directed toward improving system performance. As a subset of this effort, a five-step process was implemented by the author, post-design phase, that sought to increase performance gains at minimal cost to the user. The research approach was aggressive, and identified quantitative and qualitative areas of improvement prior to the completion of the final design specifications.

Overview of the Five-Step Research Process

The primary objective of the five-step research process executed by the author was to reduce unwanted performance variability in the KERMIIt system. This technique is often used in the aerospace industry, where extremely tight tolerances are required to produce reliable aerospace products. Implementation of variability can result in significant performance gains when implemented effectively. Conversely, large variations in system performance can result in catastrophic failures when not controlled. The process of variability reduction mirrors the scientific method, since it starts with the formation of research objectives, and a list of possible critical processes to control. The list is then narrowed down to the most critical processes, which can be influenced by cost, complexity, and performance returns. In Step Two, quantitative and qualitative data are collected on the existing system in order establish measurable (and meaningful) performance criteria. At this point the researchers must also decide upon the appropriate engineering tool for analysis of system performance. Step Three continues the process by implementing experimental techniques to establish performance variables that are sensitive to input variables, and validate system variability. In Step Four a solution hypothesis is developed using the researchers knowledge of the system, gained in Step One. Finally, the solution is implemented and validated, using experimental techniques to improve the

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system. If the desired variability is attained, the process is complete. If the desired variability is not attained, researchers must reaccomplish Step Four until an adequate solution that reduces variability is validated. It should be noted that all five steps are interdependent, and follow a build-up approach. Although all steps are equally important, Step One is the most important step, as it allows the researcher to fully develop a detailed understanding of the system and processes involved. Without a thorough knowledge of the KERMIIt system, one could not effectively accomplish Steps Two through Five.

ISS Environment

Before completing a thorough review of the KERMIIt system, a review of ISS environmental conditions is appropriate. Of course, the on-orbit environment presents a variety of thermal, structural, and mechanical challenges to engineers designing space systems. Temperature variations ranging from 200 K during darkness to about 350 K in direct sunlight places considerable design constraints on engineers designing mechanical systems in the on-orbit environment. Further, zero-g conditions also have a significant impact on ISS systems, crews, and operations. Due to its size (over 100 meters wide, and 90 meters long), the ISS is also vulnerable to impact from meteoroids and orbital debris (M/OD). Currently there are over 22,000 catalogued objects orbiting the earth, varying in size and shape (Fig. 1). NASA engineers have statistically proven that at least one significant impact will be encountered by the ISS during its ten year service life. Presentation of this information provides the initial impetus for development of an on-orbit repair system.

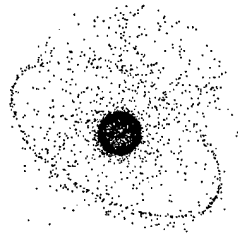


FIGURE 1. Graphical depiction of catalogued orbital debris orbiting the earth (courtesy NASA)

ISS Leak Studies

Further analysis into the probability, size, shape, and type of penetrations expected on the ISS lead engineers to characterize possible damages from the initial detection of an atmospheric leak using on-board instrumentation. Assuming the location of the leak was determined, it would then be characterized as immediate (requiring intravehicular activity to repair the leak) or temporary (requiring installation of KERMIIt). Both repairs would be followed by a permanent repair, and recertification of the ISS module for future habitation. An important point to note is that the KERMIIt system fulfills a portion of the overall ISS module recertification procedure.

APPLICATION OF STEPS 1 AND 2: UNDERSTANDING KERMIIt AND SELECTING CRITICAL PROCESSES

KERMIIt, designed by Sverdrup, Inc., provides NASA astronauts with the ability to seal small to medium size damage (maximum of four inch diameter holes, with tip-to-tip crack length of up to eight inches) in ISS modules. Full implementation of the KERMIIt system includes damage assessment, kit component assembly, and Extravehicular Activity (EVA) to prepare the damage site and install KERMIIt. The KERMIIt system consists of two types of patch assemblies, an adhesive injector system, a hole gauge and surface preparation tools (Fig. 2). The Type II patch is larger than the Type I patch, and designed for larger hole penetrations. All components are organized in a storage container for convenient assembly. When needed, astronauts open the container, put the patch into a duffel bag with the other components, and depart the station airlock to repair the damaged module.

After arriving at the damage site, astronauts clean the surface with surface preparatory tools (Fig. 2d), install the patch (Fig. 2a or 2b), connect the injector hose to connector valves within the patch, and begin injecting an adhesive using the adhesive injector (Fig. 2c) to seal the hole. The atmospheric seal is provided after the adhesive is cured. All KERMIIt installation operations occur external to ISS modules.

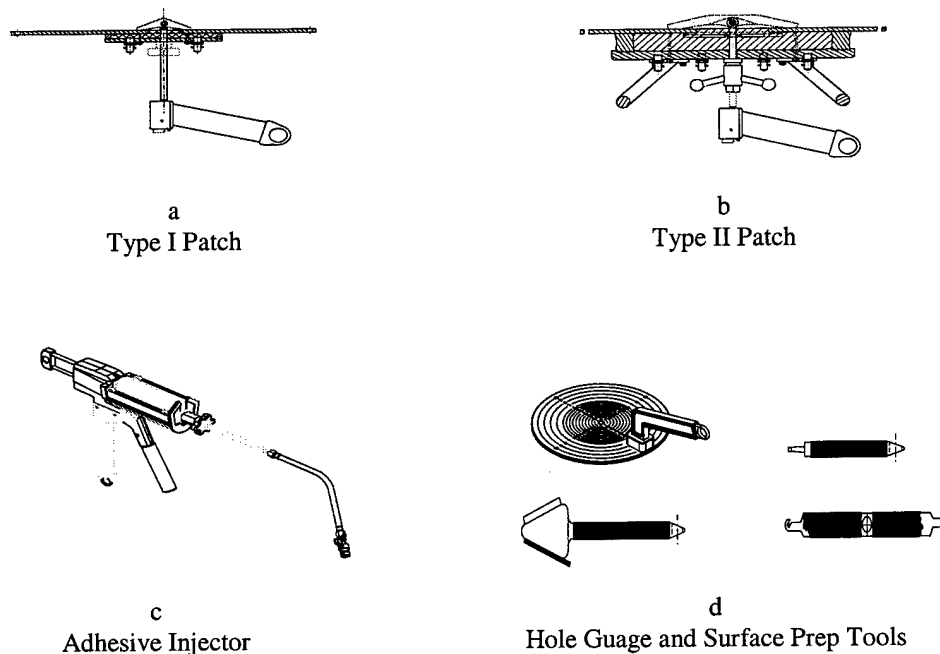


FIGURE 2. Major KERMIIt elements

The adhesive dispensed by the injector is housed in a two chamber cartridge. During injection, a two part adhesive (housed separately in each chamber of the cartridge) is mixed in the dispensing hose, causing a chemical reaction that starts the curing process. Overall, approximately thirty steps must be performed to install the KERMIIt system. Once installed, KERMIIt provides an environmental seal for the ISS module. Although the system design is robust, and the cured adhesive may provide a strong bond with the ISS skin, KERMIIt is not designed to carry primary structural loads on the ISS module.

It is important to note two major points from the review of KERMIIt. First of all, the adhesive forms the primary seal for the ISS module. Second, KERMIIt installation requires numerous steps, and manipulation of many intricate and specialized system components. Focus on these two areas of the KERMIIt system were the result of participation in multi-disciplined design reviews, requirements reviews, and technical interchange meetings, whereby design team members asked two primary questions:

1. How do we know when too much adhesive is injected?
2. Is the system too complex to install?

These two questions led researchers to focus on the flow of adhesive and crew compatibility as two critical processes which provide measurable KERMIIt performance gains when improved.

APPLICATION OF STEP 3: IDENTIFICATION OF VARIABILITY

Formation of an Adhesive Bubble

Given the selection of adhesive flow as a critical process, study of KERMI adhesive flow was directed to flight tests conducted in the NASA KC-135 reduced-gravity test platform. For each test run, the KERMI patch was installed on a sample ISS module skin with an idealized hole. Fifteen reduced gravity runs were accomplished in order to evaluate adhesive flow during the injection procedure. Flight video data was collected from four different camera angles during each thirty second reduced-gravity test run. During each thirty second test period, the adhesive was injected into the patch using the injector. For all fifteen test runs, the adhesive performed nominally, filling the KERMI patch and passing through the sample damage hole. However, repeated analysis of the video data revealed an area of potential variability.

As the adhesive passed through the idealized damage hole, the adhesive grew as if to form a bubble shape on the inside of the ISS module skin. Continued analysis of the flight video revealed variability of the end-state of the adhesive (at the end of injection). The shapes and formations of the adhesive bubble at the end-state led researchers to quantify this variability. The width and length of the adhesive were quantified by the variables X and Y as shown in Fig. 3.

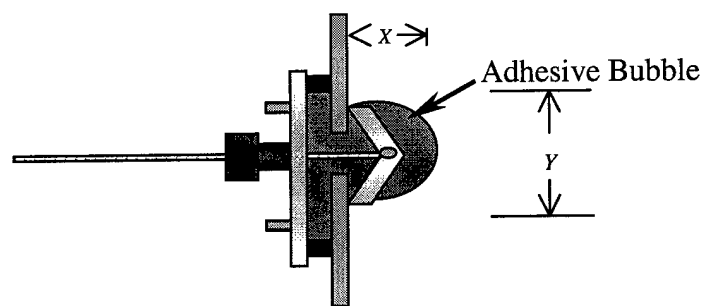


FIGURE 3. Variables used to track adhesive bubble shape

Using the flight video data, X and Y distances were extrapolated, revealing the probability density functions (PDF) shown in Fig. 4. The results showed an unacceptable variability, since too much adhesive injected would result in contact with vital utility runs, while too little adhesive injected would result in an inadequate seal of KERMI. Control of the adhesive bubble would be required to achieve the desired improvements of the system.

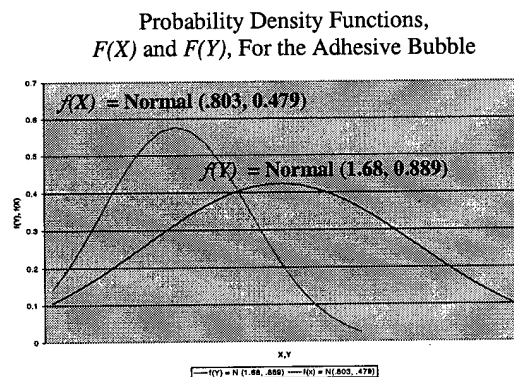


FIGURE 4. X and Y probability density functions

Mock-up Tests Used for Selection of Critical Variable

Developing critical variables to measure crew compatibility and installation effectiveness proved to be a more complex task. Crew technique, component handling, and overall compatibility with the astronaut Extravehicular Mobility Unit (EMU) had to be evaluated before recommending system improvements

based upon collected data. Initial KERMIT installation trials were conducted using idealized damage holes and the Type I patch. However, the mock-up trials were conducted without using the EMU, or space suit. Further, the reaction forces of on-orbit conditions could not be simulated. However, the mock-up installation trials did identify t , or time-to-complete individual tasks, as a critical variable.

APPLICATION OF STEP 4: DEVELOPMENT OF PERFORMANCE CONTROLS

Latex Baffle Solution

An analysis of the variables affecting X and Y revealed that adhesive temperature, viscosity, injection rate, hole type, and several other variables impacted the shape of the adhesive bubble, making control of this critical process a very complex task. However, the author chose to find a method of directly controlling X and Y , instead of controlling the variables impacting them. The result of this method was the development of a latex baffle placed on the inside of the patch (Fig. 5).

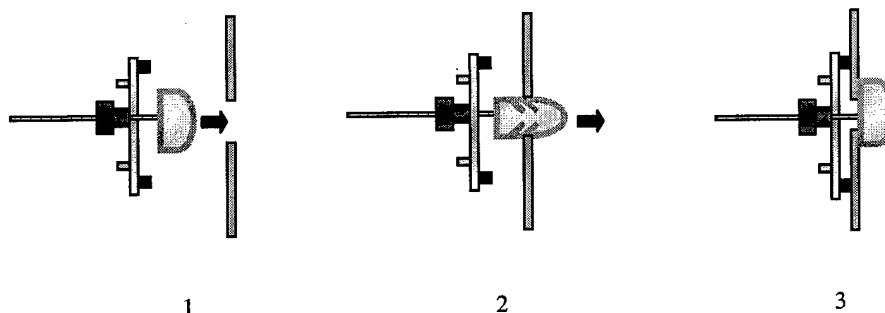


FIGURE 5. Implementation of the Latex Baffle to control X and Y

A key point to note is that the latex baffle will control the shape of the adhesive bubble independently of viscosity, position, temperature, injection rate, etc. In this respect, the latex baffle improvement was robust, and showed strong potential for improvement of the KERMIT system by using direct control of critical variables. The final step was to verify this performance improvement.

Requirement for Neutral Buoyancy Testing

Although several observations were made concerning the number of installation tasks required and overall KERMIT complexity, the mock-up trials did not have the environmental fidelity required in order to simulate on-orbit conditions. Refinement of the mock-up tests required testing in the underwater Neutral Buoyancy Laboratory (NBL) at Johnson Space Center. In the NBL, KERMIT performance was evaluated using appropriate reaction forces, an ISS mock-up, and the expertise of astronauts experienced in EVA operations. Refining the experimental techniques used in the mock-up facility, the NBL test would be able to effectively evaluate the sensitivities of system characteristics on the variable t , resulting in correlations between various input variables and their impact on t .

APPLICATION OF STEP 5: VALIDATION OF PERFORMANCE CONTROLS

Lab Verification Tests

Testing of the latex baffle concept verified the performance enhancements predicted in Step 4. Fifteen test runs were accomplished in the laboratory in order to verify the latex baffle concept. The latex baffle, when installed, enclosed the entire patch around the hole, creating a single cavity. This fact relieved the requirement for reduced-gravity flight testing. Intuitively realizing that the adhesive would simply take the shape of the rubber baffle, the author chose to conduct these tests in 1g conditions, and place the patch in various aspect angles during the injection procedure in order to prove the latex baffle would operate in a

variety of positions. In addition, a substitute adhesive was used, since it was less expensive. Adhesive curing was simulated by freezing the entire patch after dispensing the adhesive. Once frozen, the latex baffle was peeled back, and X and Y were measured (Fig. 6).

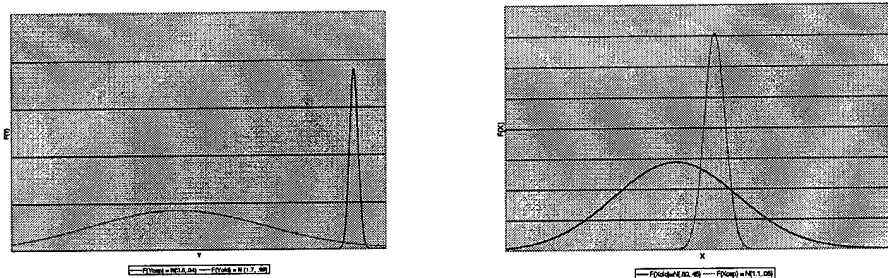
FIGURE 8. Adhesive

Neutral Buoyancy Tests

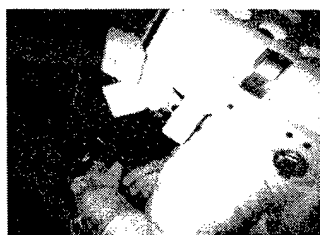
RESULTS

Patch Improvement

Crew Compatibility



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